INCONSISTENCIES IN THE UNDERSTANDING OF SOLDER JOINT RELIABILITY PHYSICS

by

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ABSTRACT

An inherent reliability problem associated with surface mount applications is that solder joints, which serve as both an electrical and a mechanical connection between part and board, are subjected to thermal fatigue failure. Solder joint failure involves a complex interplay of creep and fatigue processes. Over the years, many analytical and experimental research studies have aimed to improve the state-of-the-arl assessment of solder joint integrity from a physics-of-failure perspective. Although considerable progress has been made, there still exist many inconsistent and even contradictory correlations and conclusions.

Before discussing some of the prominent inconsistencies found in the literature, this paper reviews the fundamental physics underlying the nature of solder failure. Many inconsistencies stem from a misunderstanding of the unique properties of near-eutectic tin-lead solder, properties such as age- and cycle-softening, grain-growth hardening, strain-rate hardening and "superplasticity". Using the complex constitutive properties of solder, fundamental mechanical and thermomechanical processes can be modeled to demonstrate some of the inconsistencies in the literature. Many analytical inconsistencies are traced to differing interpretations of the effects of temperature and cycle frequency and to results obtained from using different cycle-life prediction algorithms. inconsistencies in testing arc often found when considering mechanical versus thermal cycling failure dcfi nitions, the determination of test acceleration factors, inspection techniques and objectives, and the treatment of failure statistics.

INTRODUC"I'1ON

The function of solder joints in surface mount (SM) electronics applications is to provide both electric-al and mechanical continuity between the electronic component (the "part") and the printed wiring board (PWB - the "board"). Differential expansion induced creep-fatigue resulting from temperature cycling is an important cause of solder joint failure. The deterioration of solder joint integrity typic-ally involves a sequential development of local stressing, micro-cracking, crack initiation, and crack propagation, ultimately reading in electric-al open-circuiting by total joint Separation from the PWB foot print.

The service life of a solder joint depends upon many factors, including solder alloy characteristics, the design and material selection of pm-hard assemblies, the fabrication process, and the test and service environments. The assessment of solder joint service life is a complex prows, depending, upon the application, the approach to managing solder joint integrity can differ considerably. According to published surveys [1-1 0], most current approaches rely on failure physics principles for understanding solder joint failure mechanisms and the mans to ensure solder joint reliability, the four essent ial elements of which arc: packaging design issues, solder alloy mechanical and metallurgical properties, service life prediction methodology, and testing/inspection strategies.

The state-of-the-arl of assessing solder joint reliability has not kept pace with the rapid advance of electronics packaging technology. An underlying cause is a lack of a comprehensive understanding of the fundamental reliability physics issues, Because of this, current practice to ensure solder integrity still relics heavily on design assemblies and fabrication processes that have been validated previously. Most large electronic packaging manufacturers establish their own design and fabrication procedures based typically on extensive empirical data, Interpolations of these data usually provide acceptable solder integrity assurance. Such approaches typically penalize the application of new materials and innovative designs, where extensive test data arc not yet available. For these new concepts, the assurance of solder integrity is beyond validated limits anti must rely on extrapolations using reliability physics principles.

It is the purpose of this paper to point out and to explain some of the major inconsistencies in the solder joint reliability literature. These inconsistencies, most often attributable to a failure to specify or to take into account the proper mechanical and metallurgical states of solder, arc responsible for the different conclusions that have been reached concerning solder joint inspection, quality and workmanship, life prediction, and test philosophy issues. in addition to the fact that analytical predictions of solder joint service life exhibit very large uncertainties, contradictory conclusions arc often found when considering the effects of two important environmental parameters: temperature and cycle frequency.

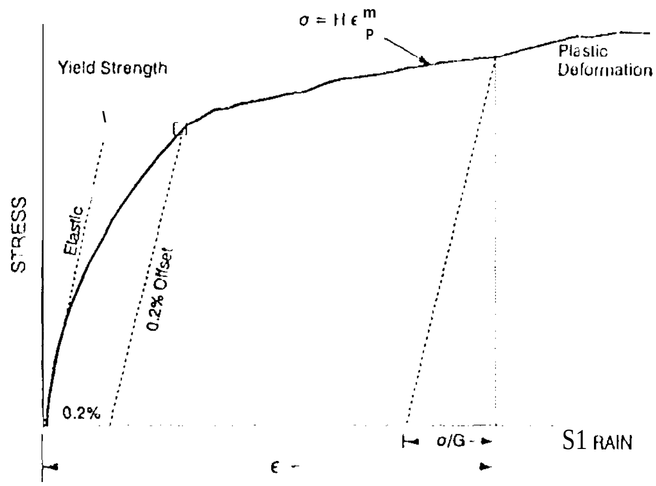
SOLDER RELIABILITY PHYSICS OVERVIEW

It will be useful to review the fundamental physics underlying solder failure and to identify the controlling parameters that contribute to the observed inconsistencies and discrepancies. The first and most fundamental parameter is the unique mechanical and metallurgical properties of solder alloys. Because near-eutectic tin-lead solder alloy (typically 63/37 by weight), having a melting point near 183°C, enjoys the widest application and acceptance in the electronics industry, the discussion is limited to that particular alloy. Secondly, the overall part/lead/board assembly stiffness and the quality of the solder joint arc the two most critical design parameters governing the reliability of solder joints in a specific service environment. Under typical multi-year loading conditions, creep induced strain is a complex function of solder metallurgical structure, stress/strain loading characteristics, solder operating temperature and the stiffness of the combined part/lead/board system,

A third factor crucial to the success (or inadequacy) of solder joint reliability assessment is the established framework of reliability physics, i.e., failure definitions, failure algorithms and the treatment and interpretation of failure statistics.

(1) Metallurgical Considerations – the Many Faces of Near-Eutectic Solder

Generally, solder is a reasonably tolerant metal with a low melting point; this makes it a desirable material for electrical interconnections. An index for characterizing operational temperature levels is the homologous temperature T_h, which is the ratio of the actual solder temperature to its melting point (absolute temperature scale). The tensile properties for a metal at low T_h arc essentially time-independent. When the applied stress exceeds the yield strength, the total strain consists of two components - elastic and plastic. The stress-stmin plot shown in Figure 1 is the most fundamental mechanical characterization of a metal.



Fig, 1, Strain Hardening for Ordinary Metals

When a metal is heated to a homologous temperature of about 0.4, the metal becomes ductile in the so-called "hot working" range. For an external stress loading the phenomenon is referred to as "creep" and for a strain loading process, the applied stress is a function of the strain rate (referred to as stmin-rate hardeni rig); "stress relaxation" and recrystallization rapidly occur. The strain-rate hardening for near-cuk'ic solder is illustrated in Figure 2, which shows the functional dependence of the stress-shain relationship on the strain rate. Elevated temperature operation is referred to as a condition for which T_h > 0.S. For near-cutectic solder at room temperature, the cm-responding homologous tcmpcraturc is 0.65, corresponding to a tcmpcraturc wcll above the rccrystallization range.

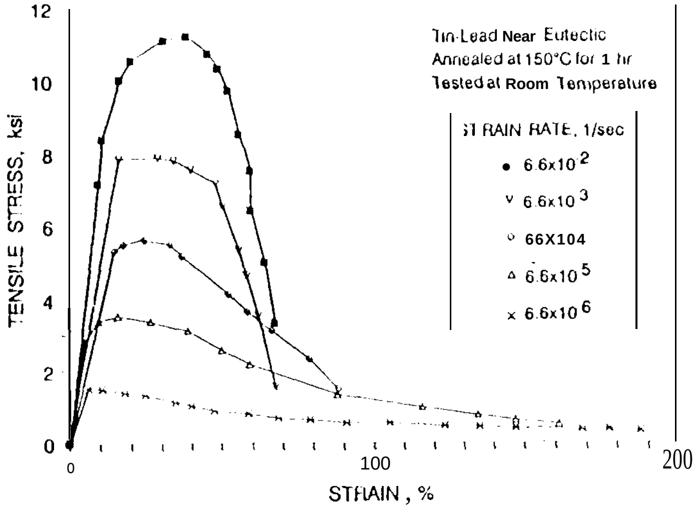


Fig 2. Strain-Rate Hardening for Near-Eutcctic Soldcr

Near-cutcztic tin-had soldcr is a metal with many faccs - its bchavior differs considerably for diffcrcnt metallurgical conditions. A newly formed solder joint is hard and brittle. Solder aged at room tcmpcraturc or otherwise heat treated, or stress cycled, is very ductile. These proccsscs arc rcfcrrcd to as agc-soflcning and Cycle-dlcning. The complctc age-softening process rcquircs about 60 days at room tcmpcraturc for the super-saturahxl tin solution to diffuse to an equilibrium slate. At room tcmpcraturc, the elongation ruptl urc limit for newly formcd soldcr is 30% to 40%, which is the same as most typical cnginccring metals. However, for a fully agc-softcncd soldcr spccimcn at room tcmpcraturc, the clongation limit is reported to bc as high as 2000% under low strain rate conditions. This makcs near-cutrxtic soldcr the best known "supcrplastic" matcrial.

The soflcning process is rclativcly rapid, especially above room tcmpcraturc. A metallurgical change concurrent with soflcning is grain growth, which is a monotonic proccss causing continuous strcngthcni ng, and at the same time cmbrittlcmcnt, of the material. Figure 3 [11] compares the microstructure of a newly formcd soldcr joint having a groin sizc of 1.8 microns to the 15 micron grain structure of a solder joint stored at room temperature for 15 years and also to a spccimcn having large 26 micron grains after one ycar of thermal cycling between -25°C and +100°C. Figure 4 summarizcs the rcprcscntativc roan tcmpcraturc property data mcasured

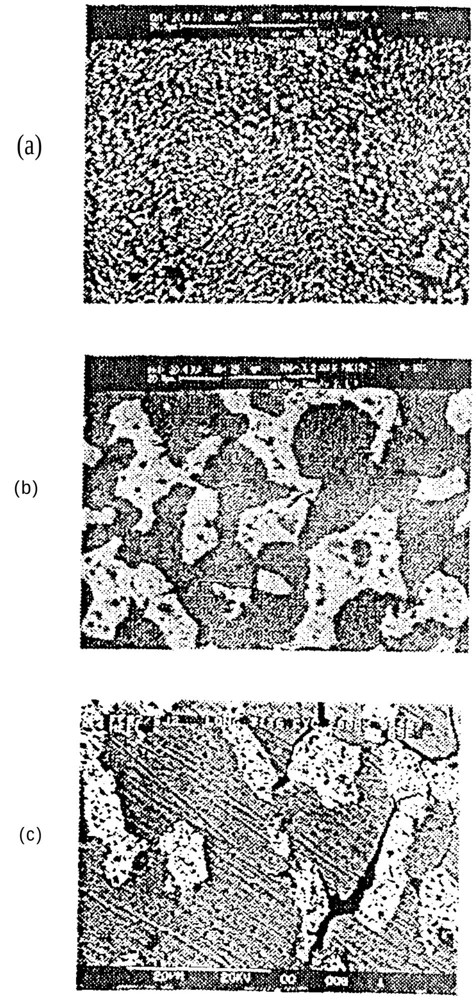


Fig. 3. Variations in Solder Joint Microstructure

by various rcscarchcrs [12-18]. The results clearly depict the diffcrcnccs in the newly formed (as-cast), fully-agcd (supcrplastic), and the over-aged (coarscncd) soldcr conditions.

Operating tcmpcraturc is another parameter that clinically affccts solder propcrtics. Figure 5 illustrates the strong Arrhcnius dcpcndcncy of solder strain rate on temperature. Soldcr bccomcs soft for conditions above room tcmpcraturc but bccomcs increasingly hard as tcmpcraturc dccrcascs. This very important consideration governs the behavior and possibly the failure of solder joints during thermal cycling,

Additional critical parameters affecting solder joint integrity assessment arc the joint quality and the

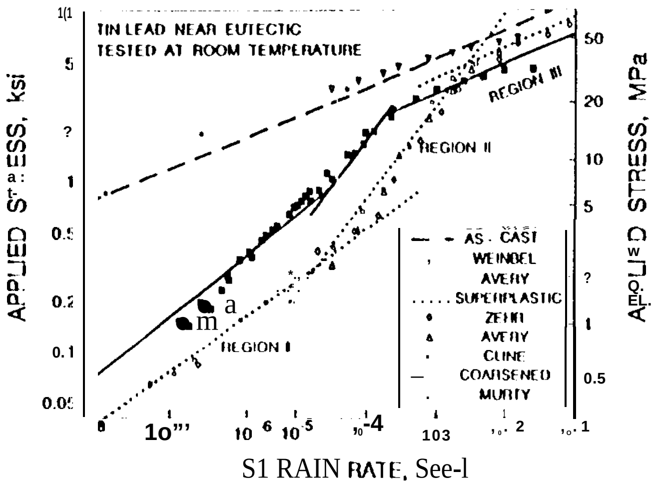
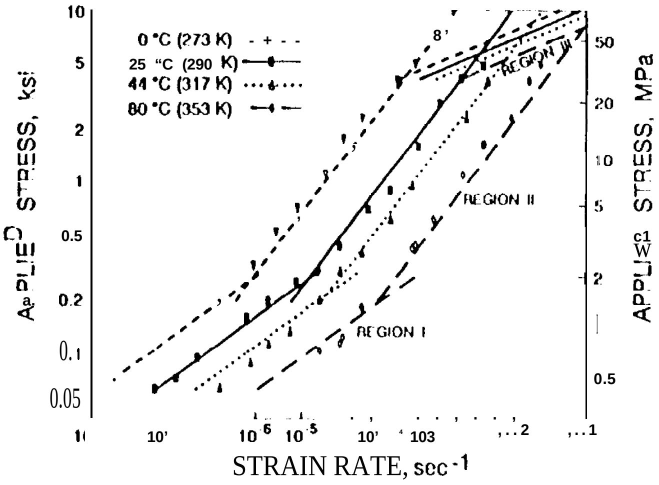


Fig 4. Microstructure Dependent Solder Creep



Fig, 5. Temperature Dependent Solder Creep

(2) Assembly Stiffness Ratio and Solder Joint Quality

For near-cukxtic solder joints operating in a specific environment, the most critical design and fabrication parameters arc the selection of the lead frame (assembly stiffness ratio) and the solder joint quality (workmanship). Electronic packaging typically involves three types of lead frames: gull-wing, J-lead and leadless (including Ball Grid Arrays). A solder joint is a structural clement that interfaces with the board and with the lead (or, for leadless unions, directly with the component). In a strain-loading process, such as is the case in thermal mechanical cycling, the driving function is a forced deformation between the PWB and the part. The total deformation is shared by the deformations of the solder joint and the fixture, consisting of the PWB and the leads. The distribution of the imposed deformation depends upon the relative stiff ıesses of the solder joint and of the fixture. A simple index that characterizes the deformation distribution is the stiffness ratio, k, [19, 19a] which is the stiffness of the combined solder-fixture system to the stiffness of the solder clement itself. A rigid fixture corresponds to the limiting case k = 1. Stiffness ratio plays a dominant role in determining the solder joint stress and strain levels. Packages with compliant leads typically have a k-value in the 0.001 to 0.0001 range, while for leadless packages k is between 0.S and 0.05.

qualification standard. The materials of which a lead/solder system arc comprised often have flaws and defects, and the fabrication proms may cause ill-formed solder joints and other imperfections. Quality inspections to screen out sub-standard parts that may lead to premature failure are typically performed following solder joint fabrication. But what is an acceptable solder joint? The terms “flaws”, “defects" and “faults” arc catch-all phrases for imperfect conditions that deviate from the desirable metallurgical state or expected workmanship of the solder joint. Not all imperfections may compromise solder joint longevity some are detrimental while others arc merely cosmetic.

In most cases, solder reliability addresses only the fabricated or repaired parts that passed the quality assurance standard, It is assured that solder joint failure is a wear-out process determined by the stress and strain levels arising only from the characteristics of the environmental input (cycle depth, ramp rate, dwell time, etc.), the relevant geometrical parameters (lead height, thickness, etc.) and material properties (Young's modulus, CTE, etc.), Consequently, the quality standard and the inspection methodology have a profound impact on the asses.wncnt of solder joint integrity and reliability.

(3) *The Physics of Solder Joint Failure*

Solder reliability physics involves many inter-disciplinary branches of science and engineering. The framework of solder reliability physics, including many of the principles and practices, arc adopted from other related established fields such as high temperat urc turbine blade failure physics and quality assurance statistics. A detailed discussion of the general aspects of solder reliability physics is beyond the intent of this paper. Only three relevant issues that contribute to the inconsistencies in the solder literature arc reviewed here. They are: (a) definitions of solder failure; (b) failure mechanisms and algorithms; and (c) treatment and interpretation of solder failure statistics.

(a) **Reliability Requirements** and Solder Failure Definitions

Solder joint qualification requirements arc typically specified in two distinctly different manners: pass/fail requirements and test-to-failruc data. Most application-oriented organizations require test qualification to meet a set of universal or mission specific pass/fail criteria. The most commonly referenced military requirement is the maintaining of functional integrity (no electrical open-circuiting) after 1000 cycles of the MANTECH [20, 21] environment between -55°C and + 125°C per MIL-STD-883, Method 1010 [22]. The qualification requirement has been adopted to ensure avionics integrity for a 20-year service life of 8,000 flights and 4,000 maintenance hours. The requirement for NASA space missions is specified in NASA NHB 5300.4 [23] as 200 cycles between -55°C and + 100”C without the initiation of cracks. In recent years, the adopted Qua] test requirements have been based upon specific missions. For example, the requirement for Cassini transponder packaging is 100 cycles between -25°C and +100°C with the extent of crack propagat ion to be limited to less than 1/3 of the solder joint periphery.

Most research laboratories and universities have adopted a test-to-failure approach, which provides basic failure physics insight, allowing better understanding and knowledge of solder joint reliability issues, Because the test time can be very long for most robust designs, the practice of test-to-faihrrc is usually conducted on an accelerated basis. There have been many different measurement techniques for detecting solder failure [1, 3, 59], Monitoring electrical continuity is the most definitive method of detecting solder joint failure for thermal mechanical testing and has been recommended by IPC [24, 25]. A sequence of periodic in-test visual inspections for tracking crack growth is a common technique [26]. Another popular measure is the 50% loaddrop measurement [43], which has been adopted by many researchers for room temperature mechanical cycle testing [27, 28]. The difference in failure definitions and the measurement techniques can be a serious source of confusion when comparing experimental results,

(h) **Principles** and Algorithms in **Failure** Physics

The algorithms used in solder research are typically adopted from related research fields, especially high temperature pressure vessel and turbine blade research [29-32]. Although there arc many variations and modifications, the fundamental failure algorithms can be categorized into four major approaches: (1) stress-based; (2) slrain-range-based; (3) strain-energy-based; and (4) fracture-mecha nics-based. The selection of a particular algorithm not only lays down a speci tic framework for analytical treat ment of the reliabil ity research, it often prc-sets the format and control variables for experimental investigation.s. . in most applications the usage of different failure algorithms is compatible. However, there arc cases for which inconsistent and even contradictory conclusions may be reached depending upon which algorithm is selected.

(c) Failure Statistics

The service life of solder joints on a surface mounted part is dictated by the weakest solder joint, since the failure is referenced to the first interconnect failure on an assembly. The corner joints arc particularly vulnerable, not only because they experience the maximum deformation, but also because the fillet size at the corner is, in general, smaller than at the middle, Among the corner joints a noticeable difference in fillet size (around 10% to 20% fillet thickness) can often be observed. These variations definitely contribute to the spread of the solder joint statistical failure distribution, whose range can extend over more than an order of magnitude. The majority of investigators utilize a Weibull distribution [25, 32] to characterize the spread of solder joint failure data. The application and interpretation of the statistical manipulations arc very crucial to the process of ensuring solder joint integrity but at the same time cause much confusion.

INCONSISTENT ISSUES

The inconsistencies observed in the literature can generally bc grouped into three categories: (I) different opinions and conclusions concerning behavioral fundamentals; (2) conflicting correlations or significant discrepancies with regard to major reliability issues; and (3) inconsistent correlations established for practical applications, The first category covers many issues relating to solder properties, analytical modeling, and differences in terminology and definitions, while the last category covers real life applications and is most critical to the practice of solder joint reliabilit y.

(1) Fundamental Inconsistent Issues

In the solder reliability literature, numerous statements or concluding remarks made by onc group of researchers arc contested by another. Since many such contentions have more academic interest than practical significance, the issues they raise arc only briefly addressed in this sub-section.

In the first category of contentions arc such highly debated topics as:

(1) Is high strength or high ductility the more desirable solder property?
(2) What role, if any, do intermetallics play in solder joint failure?
(3) Is crack initiation a useful fatigue failure index? Is load drop measurement together with straddle board an effective indicator of assembly reliability index?
(4) What effect do voids have on solder joint failure?
(5) What effect does temperature wave form (ramp rate and dwell time) have on solder joint failure?
(6) Describe solder behavior at sub-zero temperatures.

Contentions in this category reflect uncertain information more so than inconsistent observation.

A second category of contentions has a more far-reaching impact; they arc in fact inconsistencies in interpretation and can lead to different approaches or different practices to ensure solder joint integrity, A few such typical sources of inconsistency arc:

(a) plastic strain vs creep - For most metals there is a relatively wcI1-defined transition between elastic and plastic deformation; not so for solder, for which the tensile strength, and hence the yield strength, is a strong function of strain rate and metallurgical conditions, Fig, 6 [13, 33-38]. So when does the onset of plastic strain occur? Plastic deformation is not a time-dependent phenomenon, whereas creep deformation is. Mosi materials creep slowly; solder creeps quickly. Different researchers use different combinations of elastic, plastic, and creep straining to describe solder behavior [1, 39-41] often without a sound means of differentiating between plastic and creep straining.

(b) Graininess - The usual definition of graininess is an unacceptable solder surface condition resulting from contamination during reflow operations, producing a gritty surface [42]. This is to bc contrasted with the condition of large grains, a possibly acceptable metallurgy.

(c) The merit of isothermal mechanical cycling - Can room temperature mechanical cycling bc substituted for thermo-mechanical cycling to eliminate time-consuming and expensive testi ng? Because of its simplicity, iothermal testing has often been performed in place of the more complicated thermal cycling [43-46]. But there arc major differences, Fig. 9. Stress-strain hysteresis loops for isothermal mechanical cycling differ significantly from those for thermo-mechanical cycling. The former exhibit symmetries that the latter do not, Furthermore, creep ratcheting is not a factor in isothermal mechanical cycling, whereas it is in thermo-mechanical cycling

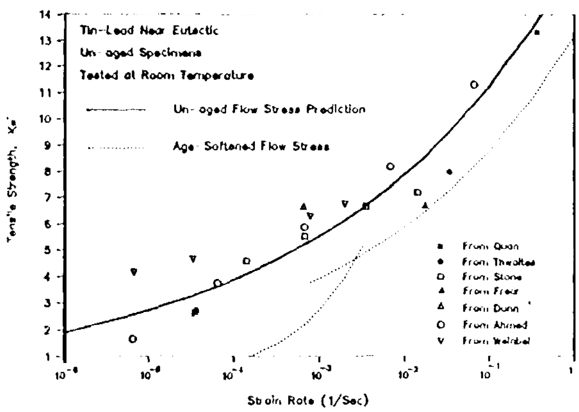


Fig. 6, Tensile Strength of Unaged Solder at Room Temperature

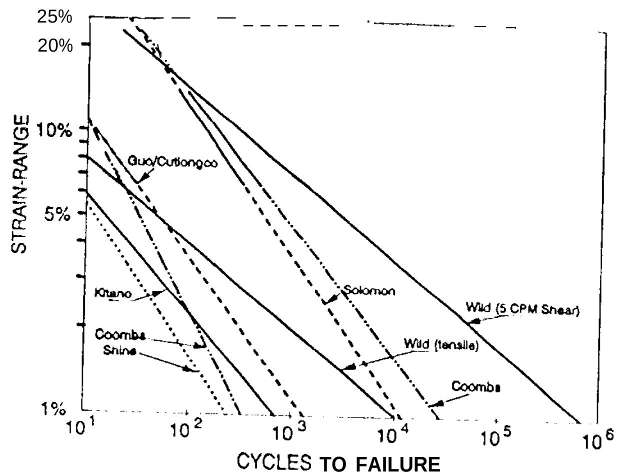
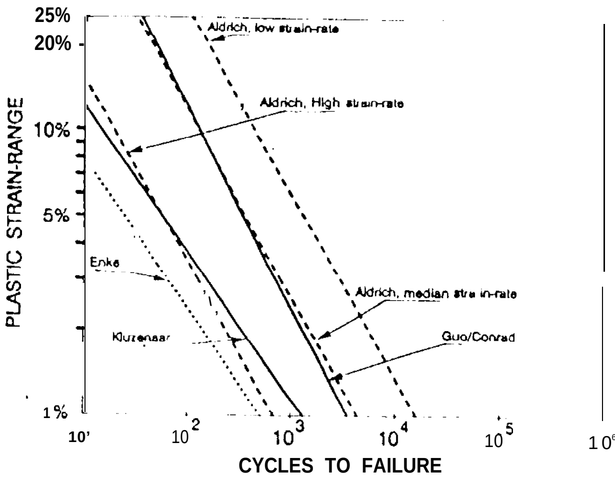
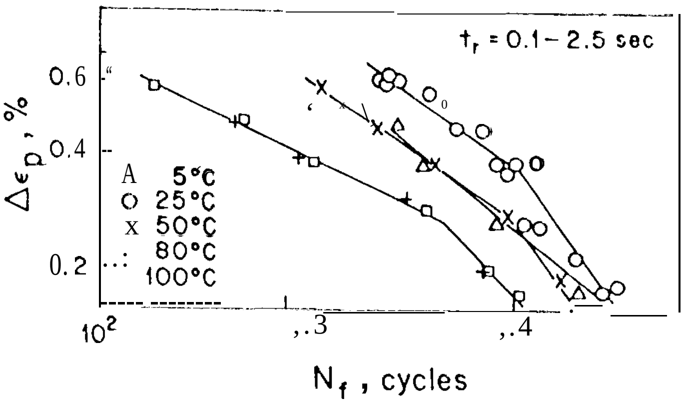


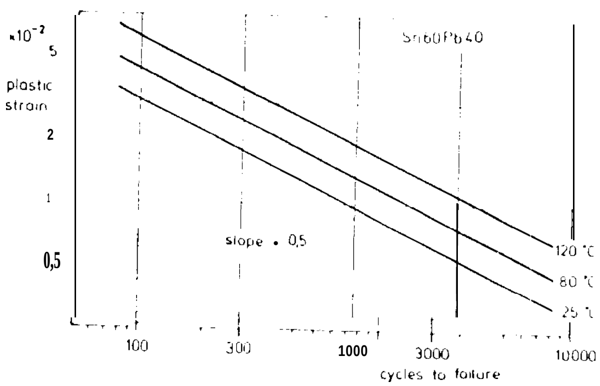
Fig. 7a. Comparison of Solder Fatigue Data



Fig, 7b. Selected Solder Fatigue Correlations



Fig, 8a. Experimental Fatigue Curves - 50% Load Drop Failure Criterion



Fig, 8b. Experimental Fatigue Curves - Fracture Failure Criterion

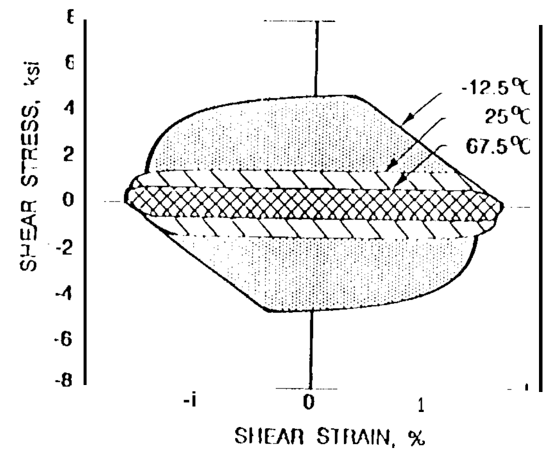


Fig. 9a, Strain Energy Density - Mechanical Cycling

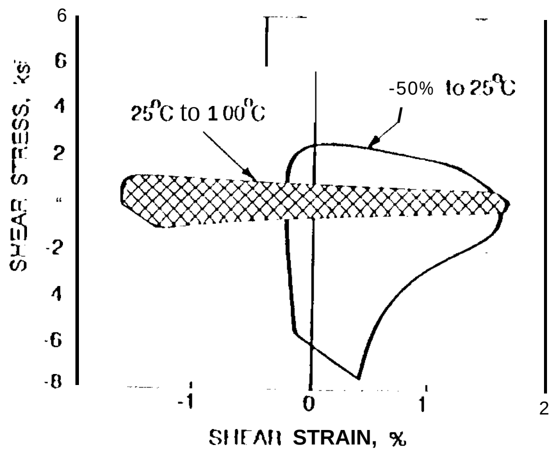


Fig. 9b. Strain Energy Density - Thermal Cycling

(2) Major Discrepancies

(a) <u>**Coffin-Manson** Correlation and **Solder** Joint Failure Data **Base**</u>

Most experimental cycle fatigue failure data derive from **mechanical** cycling at room **temperature**. The results are typically **presented** as strain versus cycle-to-failure in a **Coffin-Manson** format. Figures 7-a and 7-b compare published experimental **near-eutectic** solder data **gathered** by various **researchers** [2, 27, 47-57]. The most quoted solder joint failure data are those of **Coombs** [47] and Wild [48, 49] generated at IBM approximately two **decades** ago. The two sets of data by **Coombs** (torsion **vs** shear lap) **reflect** a **difference** as **large** as two orders of **magnitude** in fatigue life for a **specific** strain range level. Similarly, the test data obtained by Wild show the same type of variations. The cycle-to-failum level for a 1'%0 slrain-range changes from a low value of 330 (torsion test data by Combs) to a high value **of** 700,000 (5 **cpm** shear data by Wild) - a **discrepancy** of 200,000 **%**. It is **recognized** that many of the-w data may be tainted **with** serious **experimental** flaws - the failure **definitions** were not **consistent** and the **metallurgical** conditions of the **solder** samples (freshly **formed** vs age softened vs grain **coarsened**) were **not the** same. In Figure 7-b a subset of the reported **test** data is plotted; the **subset** includes those data which **reflect** similar **experimental** approaches and **control** of **solder** aging. Note that even with this normalization, significant inconsistencies **remain**.

(b) <u>**Temperature** Effect</u>

Temperature level is a very critical **determinant** of solder mechanical properties and **behavior**; it is natural to **expect** that **solder** temperature plays an important role in solder joint failure. A number of researchers have investigated the **effect** of **temperature level** on the **cycles-to-failure** for **isothermal** mechanical cycle **testing**. **Figures** 8-a and 8-b are the test results **presented in terms of inelastic strain range vs cycle-to-faihrrc. Figure 8-a was obtained** using a **50%** load drop definition for cycling at 0.3 Hz. Solomon and **Vaynman** [43, S8-61] concluded that with decreasing solder **temperature**, the cycle-to-failure number **increases**. Figure 8-b **was** obtained using a fracture **definition** on tensile **specimens with** a cycle period of **15** minutes. **Wassink** and **Neijen/Kluizennar** [2, 62] concluded that with decreasing solder temperature the cycle-to-failure number **decreases**.

As a means of removing experimental error and failure definition **as** possible causes for this apparent **discrepancy**, the **classical** analytical treatment of a **leadless solder joint** undergoing **mechanical** cycling **can** be **reviewed** as follows: Figures 9a and 9b show hysteresis plots for mechanical cycling at different **temperature** levels and for thermal cycling [63]. An analytical prediction using **Engelmaier's** equation [64-67] **results** in an **increase** in cycle **life** at low

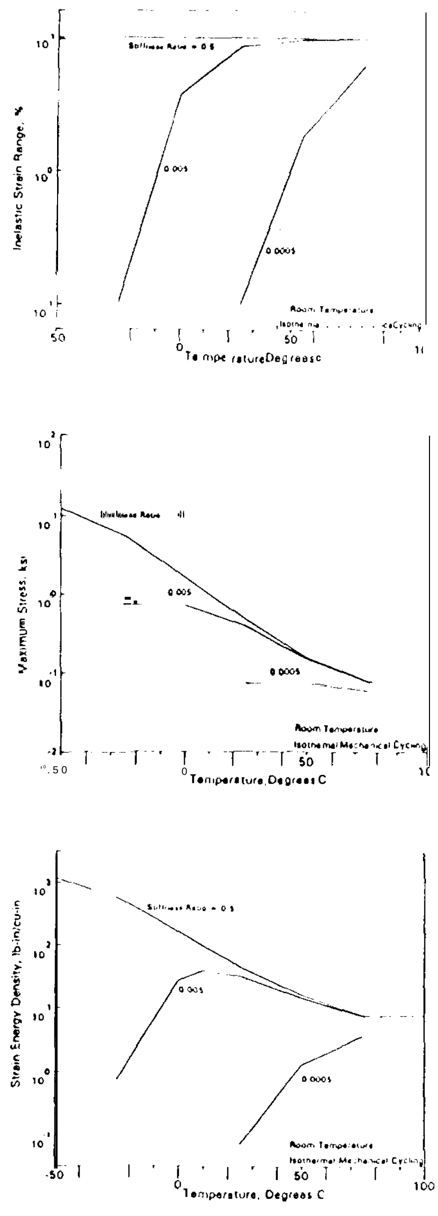


Fig. 10. Isothermal Mechanical Cycling: Stiffness and Temperature Dependency

temperatures. However, if the basic Coffin-Manson equation is used, the prediction is essentially no change in cycle life at different temperatures. Finally, based on the strain-energy density algorithm [7, 59, 68-71], which states that cycle damage is proportional to the energy density, i.e., the hysteresis area, the prediction is a decrease in cycle life at low temperatures.

Two of the three algorithms must be non-applicable to the case considered. On the other hand, the discrepancy demonstrated in the experimental data may have a logical explanation. One such explanation may lay in the difference in system stiffness ratios. In a recent study [72], a computer simulation of solder joint isothermal mechanical cycling (period = 3 hours) was performed to calculate the strain energy dens.ity as a function of solder temperature for different stiffness ratios. Figure 10 illustrates that for cases with high stiffness ratio (e.g., LCCs), the strain range is independent of temperature, but the maximum solder stress and strain energy density decrease monotonic-ally as temperature increases. On the other hand, for systems with low stiffness ratios (e.g. compliant gull-wing packages), solder strain range decreases with decreasing temperature while the maximum solder stress remain low and dots not vary significantly with temperature. The strain energy density increases with temperature. For systems with intermediate stiffness ratio there may be a temperature level for maximum strain energy densit y. If one utilizes strain energy density as a measure of cycling damage and thus as a determinant of cycle life, then the effect of temperature can be positive or negative depending upon the temperat urc level and the system stiffness ratio.

(c) Frequency Effect

Cycle frequency is another important determinant of solder creep/fatigue behavior [1, 19]. Similar to the temperature effect, literature reports concerning cycle frequency are not consistent. Figure 11-a, for 35°C cycling, shows that for a specific strain range, the solder cycle life decreases with decreasing frequency [43, 59, 73-76]. On the other hand, the test data by Aldrich and Avery [56], Figure 11 - b, indicate just the opposite.

Both Figures 1 1-a and 1 1-b arc for strain-loading cycling using strain-range as the only driving parameter. For stress-loading cycling, the failure data arc typically expressed as a classical S-N plot as shown in Figure 12 [78]. For a specific stress level, a decrease in frequency results in a decrease in cycle life. However, in a strain-loading condition, the stress level may vary Considerably based on the system stiffness ratio and solder temperature. Figure 13 illustrates a simulated result [72] for isothermal mechanical cycling at room temperature as a function of frequency and system stiffness. It is noted that for a high stiffness ratio (e.g., LCCs), the maximum solder stress and strain energy density decrease as frequency decreases. But, for low stiffness ratios (compliant leaded packages), the strain energy density increases as cycle frequency decreases.

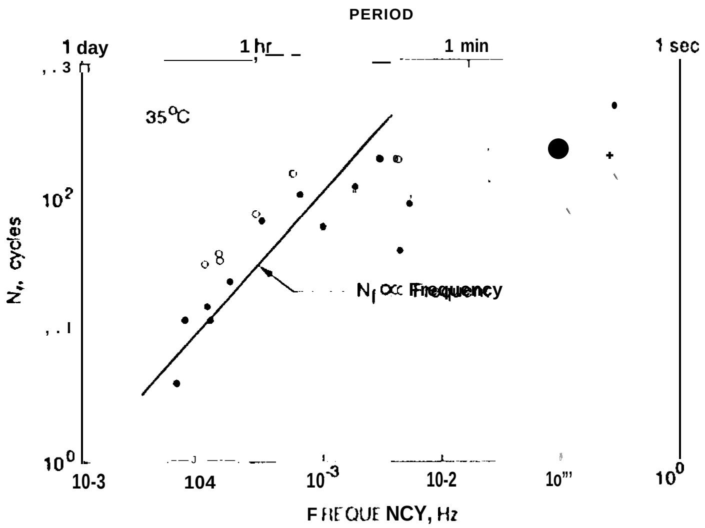


Fig. 1 1a. Cycles-to-Failure vs Frequency -- Strain Loading

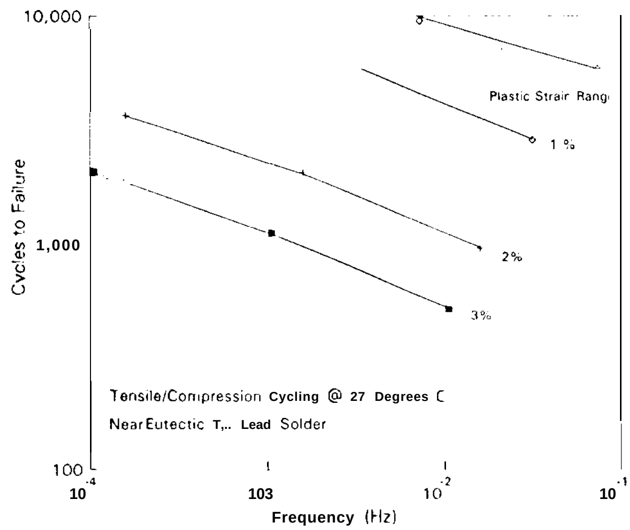


Fig. 1 lb, Cycles-to-Failure vs Frequency -- Strain Loading

(3) *Inconsistencies in Applications*

(a) Service Life Predictions

A diverse collection of solder joint life prediction analyses arc to bc found in the literature. They range from simple formulas derived from the Coffin-Manson equation to very complicated finite element models. Accurate prediction of solder joint service life is very difficult because of the complex tcnqx.mature-time dependence of solder properties. Furthermore, because of the large number of variables, most schemes for solder joint service life prediction differ considerably. As a consequence, there arc large variations in service life predictions for the same physical system. Many factors contribute to the large uncertainties in solder joint service life predictions. These include variations in the physical model representation, disagreements in solder property algorithms, and the disparity in failure algorithms and prediction schemes. Two particular factors amplify the inconsistencies. One factor is the very definition of failure. Many analytical predictions arc based upon crack initiation at local stress-concentrations. Other more realistic predictions arc based upon separation of the joint as a result of 100'%0 crack propagation. The two predictions can differ by an order of magnitude. The other factor is the statistical interpretation of analytical predictions. Most analytical predictions arc based upon mean cycles to failure, i.e., 50% failures. However, many companies elect to predict early failure (i.e. 3% to 9% failure) for added safety margin.

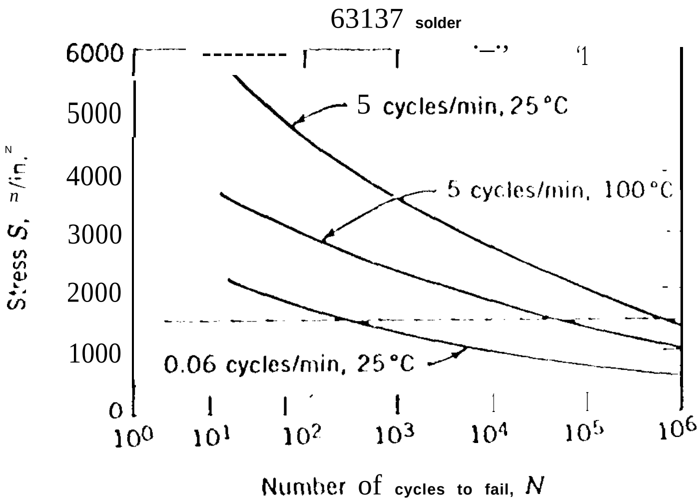


Fig. 12. Cycles-to-Failure vs Stress - Stress Loading

(b) Acceleration Factor

The transformation relationship between accelerated thermal cycle testing and field service application is a most critical issue in reliability testing. Power law relationships such as $(N_1/N_2) = (AT_2/AT_1)$" have typically been used as a basis for deriving acceleration factors [6, 78-8 1]. The ratio of the accelerated test to field CTF (cycle-to-failure) is correlated to the ratio of field to accelerated test temperature cycle depth by the

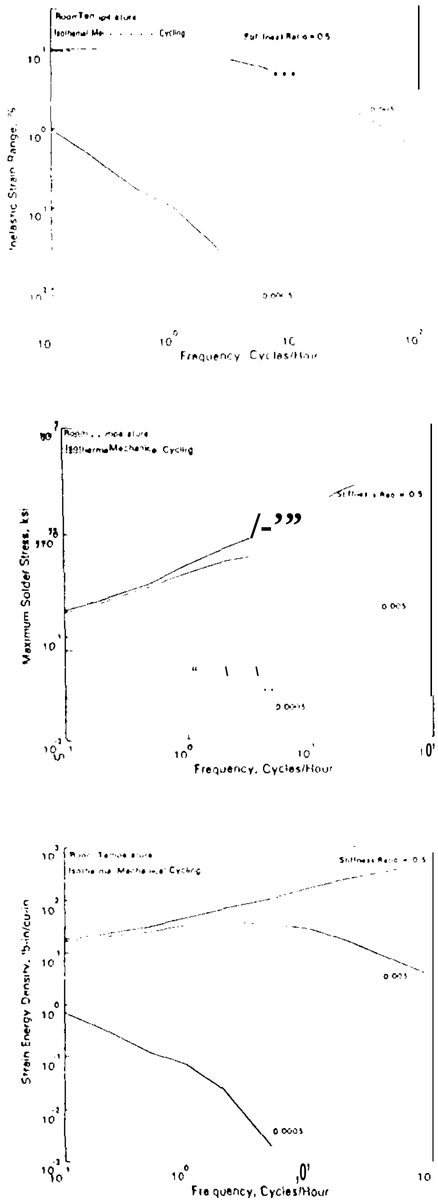


Fig. 13. Isothermal Mechanical Cycling: Stiffness and Frequency Dependency

acceleration exponent 'b". A suitable value for the acceleration exponent has been the subject of many heated debates. Unfortunately a small change in the acceleration exponent can result in significantly different qualification test cycle lengths and strongly impact cost and test schedules. For example, a representative electronic system for a flight electronic board is assessed to experience an equivalent of 2455 cycle.s, each with a 15°C temperature fluctuation. To qualify the hardware with a typical NASA NHB cycle (from -55°C to+ 100°C in 4 hours) and factor of safety of 10, the required qualification test cycle can be determined from the power-law correlation to be 24 55x10/(155/15)^b. Depending upon the selection of the exponent value, the qual test requirement may range from 57 cycles (or 10 days) for a JPL referenced exponent value of b = 2.6, or 230 cycles (38 days) for Norris-Lanzbery [78] exponent of b = 2, to a very conservative 2375 cycles (396 days) corresponding to a b-value of unity.

1'0 further Complicate the issue, there arc experimental reports indicating that the acceleration factors for small strain ranges (field service applications) arc different from those for large strain ranges (accelerated testing). For example, Vaynman & Zubelelewicz [82] observed that the Coffin-Manson exponent based upon high strain range data, when extrapolated to lower strain ranges, over-predicts service life for applications with inch.lic strain ranges less than 0.280/6 On the other hand, investigators from Hitachi observed the opposite, i.e., extrapolating the accelerated test exponent to the low strain range region under-predicts service life.

(c) k-liability Quotient

The application dictates the means whereby solder joint reliability is determined. As regards this, the military MANTECH requirements have previously been mentioned. For commercial and industrial applications, failure statistics in terms of parts-failure-per-million during a certain service period are obtained from field surveys and is an index associated with profit margin and company reputation, Space applications impose several unique solder reliability issues: ultra-small quantities, highest reliability requirements, and diversified environments with minimal feedback from field operations. The reliability is associated with the first failure of an electronic part or its interconnections. However, it is extremely difficult to quantify the reliability requirement, A required reliability quotient of 0.9999 for a total of ten or twenty parts in use is often nothing more than an abstract notion, The process of qualification testing to demonstrate the required reliabilit y often varies from project to project. Because of the lack of an established comprehensive methodology, the demonstrated reliability may vary by orders of magnitude depending upon the knowledge of tbc QA individuals and the cost/schedule pressures of the project.

CONCLUDING REMARKS

Onc major deficiency in assessing solder joint integrity has been the lack of a consistent and comprehensive understanding of the underlying physics. Partly responsible is the publication in the solder literature of contradictory test data. Because solder joint failure is a very complex process, involving (too) many variables, it is extremely difficult to correlate the test results from two independent tests. A case in point is the solder research activities performed for NASA at JPL. The experimental program evolved through several phases. Even with a closely collaborative research team, the fabrication procedures, the test method and the failure detecting techniques were not calibrated to ensure continuity from onc phase to the next. Although much was learned about the mechanical behavior of solder and its failure physics, the rc.suits have nonetheless been very disheartening. Not only did the failure test data show discrepancies, failure predictions considerably missed the mark - even for experiments specifically designed to resolve the issues of effects of temperature and accelerat ion factor. The experimental results did not display dependency on mean temperature nor did they confirm the commonly used (at JPL) acceleration exponent of 2.6. The results showed that cycle-to-failure is linearly proportional to time in the chamber, with an exponent close to unity. There have been many critiques about the experimental and fabrication issues. A review of the test program revealed facts such as (1) the quality of the solder joints were purposely not screened *a priori* and (2) the solder fillets of some of the LCC parts were unacceptably insufficient because of the improper use of solder mask. The sad conclusion is that the research program did not provide conclusive answers. Why? It was conjectured that the pressure to cut costs and rapidly obtain results ('cheaper, faster') led to an overly ambitious experimental program, It addressed too many issues at once, without allowing time to calibrate the experimental setup with those conducted in earlier phases. It adopted so many independent variables that adequate statistical sample size was compromised. It turned out that this particular effort undertaken to resolve some of the uncertainties in understanding solder behavior actually generated more uncertainy.

REFERENCES

[1] Sandor, Bela I., "Life Prediction of Solder Joints: Engineering Mechanics Methods," Chapter 8 Solder Mechanics - A State of the Art Assessment, Edited by Frear, D.R., et. al., TMS publication 1990.

[2] de Kluizenaar, E, E., "Reliability of Soldered Joints: A Description of the State of the Art," Soldering & Surface Mount Technology, No. 4, Feburary 1990 (Part 1); No. 5, June 1990 (Part 2); and No. 6, October 1990 (Part 3).

[3 Hacke, P. L., Sprecher, A. F. and Conrad, H., "Thermomechanical Fatigue of 63Sn - 37Pb Solder Joints," in Thermal Stress...and Strain in Microelectronics Packaging, Edited by Lau, J. H., Van Nostrand Reinhold, 1993.

[4] Stockrnan, S. B. and Coit, D. W., "Surface Mount Technology: A Reliability Review," IIT Research Institute RADC/RAC SOAR-5, 1986.

[5] LAO, J. H., "Surface Mount Solder Joints under Thermal, Mechanical, and Vibration Conditions," in Mechanics of Solder Alloy interconnects, Edited by Frear, d. al., Van Nostrand Reinhold, 1994.

[6] Ross, R G. Jr., "A Systems Approach to Solder Joint Fatigue in Spacecraft Electronic Packaging," J. Electronic Packaging, Vol. 113, pp. 121-128, June 1991.

[7] Darveaux, R, Nanerji, K., Mawer, A, and Dody, G., "Reliability of Plastic Ball Grid Array Assembly," Ball Grid Array Technology, Edited by J. H. Lau, McGraw Hill, 1995.

[8] Barker, D., Vodzak, J., Dasgupta, A, and Pecht, M., "Combined Vibrational and Thermal Solder Joint Fatigue - A Generalized Strain versus Life Approach," J. Electronic Packaging Vol. 112, pp. 129-134, June 1990.

[9] Hwang, J. S., "Solder Paste in Electronic Packaging," Van Nostrand Reinhold, 1989.

[10] Kilinski, T. J., Lesniak, J. R and Sandor, B., "Modem Approaches to Fatigue Life Prediction of SMT Solder Joints," in Solder Joint Reliability, Edited by J. H. Lau, Van Nostrand Reinhold, 1991,

[11] Wen, L. C., Men, G. R, and Ross, R G., "Metallurgical Variations in Near Eutectic Tin-Lead Solder During Thermal-Mechanical Processes," JPL D-9632, 1992.

[12] Arrowwood, R., Mukherjee, A., and Jones, W. B., "Hot Deformation of Two Phase Mix-lures," Solder Mechanics: A State of the Art Assessment, Minerals, Metals and Materials Society, Warrendale, PA, pp. 107-153, 1991.

[13 Weinbel, R. C., Tien, J. K., Pollak, R A., and Kang, S. K., "Creep-Fatigue interaction in Eutectic Lead-tin Solder Alloy," J. Material Science Letter, Vol. 6, pp. 3091-3096, 1987.

[14] Avery, D. H., and Backofen, W. A., "A Structural Basis for Superplasticity," Transaction of the ASME, Vol. 58, pp. 551-562, 1965.

[15] Zehr, S. W., and Backofen, W. A.,"Superplasticity in Lead-Tin Alloys," Transactions of the ASME, Vol. 61, pp. 300-312, 1968.

[16] Clint, H. E., and Alden, T. H., "Rate Sensitive Deformation in Tin-Lead Alloy," Transactions of the ASME, Vol. 239, pp. 710-714, 1967.

[17] Murty, G. S., "Stress Relaxation in Superplastic Materials," J. of Material Science, Vol. 8, pp. 611-614, 1973.

[18] Kashyap, B. P. and Murty, G. S., "Experimental Constitutive Relations for the High Temperature Deformation of a Pb-Sn Eutectic Alloy," Material Science and Engineers, Vol. 50, pp. 205-213, 1981.

[19] Ross, R. G., Jr., and Wen, L,., "Solder Creep-Fatigue Interactions with Flexible Leaded

Surface Mount Components, 'Thermal Stress and Strain in Microelectronics Packaging, Edited by John H. Iau, Van Nostrand Reinhold, 1993, pp. 607-647.

[19a] Wilcox, J. R, Subrahmanyan, R, and Li, C-Y., "Assembly Stiffness and Failure Criterion Considerations in Solder Joint Fatigue," J. Electronic Packaging, Vol. 12, pp. 1115-1121, June 1990.

[20] Root, J. A.,"MANTECH for Advanced Data/Signal processing- Vol. IV Final Report for Tasks IV and V Module Demonstrations," WRDC-TR-89-8025, vol. IV, Dec. 1990.

[21] MANTECH for Advanced Data/Signal Processing" WRDC-TR-89-8025, 1991.

[22] "Military Standard-Test Methods and Procedures for Microelectronics," Department of Defense, MIL-STD-883C, Aug. 1983, MIL-STD-883B Aug. 1977.

[23] NASA, "Requirements for Soldered Electrical Connections," NHB 5300.4 (3A-I), Revalidated date: June 1986.

[24] "Design Guidelines for Reliable Surface Mount Technology Printed Board Assemblies," IPC-D-279, IPC 1992.

[25] "Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachment," IPC-SM-785, Institute for Interconnecting and Packaging Electronic Circuits, Lincolnwood, 11,., Nov. 1992.

[26] Wen, L. C., Men, G. R, and Ross, R G., "Investigation of Crack Propagation in Solder Joints on Gull-wing Lead Flat-Pack Components," JPL D-10917, July 1992.

[27] Solomon, H. D., "Low Cycle Fatigue of 60/40 Solder - Plastic Strain Limited vs Displacement Limited Testing," Proceedings of ASM's 2nd Electronic Packaging: Materials and Processes Confer'cnn Bloomington, Minn, Oct. 1985, pp. 29-47.

[28] Zubelewicz, A., Guo, Q., Cutiongco, E. C., Fine, M. E., Keer, L. M., "Micromechanical Method to Predict Fatigue Life of Solder," J. Electronic Packaging, Vol. 112, June 1990, pp. 179-82.

[29] Coffin, L. F. Jr., "A Study of the Effects of Cyclic Thermal Stresses on a Ductile Metal," Trans. ASME, Vol. 76, 1954, pp. 931-950.

[30] Manson, S. S., "Behavior of Materials Under Conditions of Thermal Stress, "Heat Transfer Symposium, University of Michigan Engineering Research Institute, 1953, pp. 9-95.

[31] Manson, S. S., Halford, G. R, and Oldrieve, R E., 'Relation of Cyclic Loading Pattern to Microstructure] Fracture in Creep Fatigue," NASA TM 83473, Sept. 1984.

[32] 1 au, J., et al., "Experimental and Statistical Analyses of Surface Mount Technology PLCC Solder Joint Reliability," IEEE Transaction on Reliability, Vol. 37, No.5, 1988, pp. 524-530.

[33] Quan, L. K., "Tensile and Shear Behavior of Alloyed Sb-Pb Solder Joints," M, S. Thesis, IJ31.-25741, August 1988.

[34] Thwaites, C. J., Warwick, M. E., and Scott, B., "Tin and Tin Alloys" in Metallography and Microstructures. Metal Handbook, 9th Edition, Vol. 9, ASM, 1985, pp. 449-457.

[35] Stone, K. R, Duckett, R, and Warwick, M., "Mechanical Properties of Solders and Solder Joints," Brazing and Soldering, No. 4, 1983, pp. 21-27.

[36] Frear, D. R, "Microstructural Observations of the Sn-Pb Solder/Cu System and Thermal Fatigue of the Solder Joint," Ph.D. Thesis, U. C, Berkeley, 1987, LBL-23879, DE88 001392,

[37] Dunn, B. D., "The Properties of Near-Eutectic Tin/Lead Solder Alloys Tested Between +70 "C and -60°C and the Use of Such Alloys in Spacecraft Electronics," European Space Agency Report ESA TM-162 , (ESTEC), September 1975.

[38] Ahmed, M. N., and Langdon, "Ductility of the Superplastic PbSn Eutectic at Room Temperature," J. Material Science Letters, Vol. 2, 1983, pp. S9-62.

[39] Dasgupta, A., Verma, S., and Barker, D., "Fatigue Life of Misregistered J-Lead Solder Joints Through an Energy-Partitioning Analysis," presented at the ASME Winter Annual Meeting, Anaheim, CA, 92-WA/EEp-28, 1992.

[40] Barker, D., et al., "Combined Vibrational and Thermal Solder Joint Fatigue - A Generalized Strain Versus Life Approach," J. Electronic Packaging, Vol. 112, pp. 129-134, June 1990.

[41] Ross, R G., and Wen, L.," Crack Propagation in Solder Joint During Thermal-Mechanical Cycling," presented at the ASME Winter Annual Meeting, New Orleans, Louisiana, 93-WA/EEP-9, November 1993.

[42] Bulwith, R. A., "The Rough or Grainy Solder Phenomenon," Printed Circuit Assembly, pp. 10-14, March 1987.

[43] Vaynman, S., Fine, M. E., and Jeannotte, D. A., "Low-Cycle Isothermal Fatigue Life of Soldered Materials," Solder Mechanics, Edited by Frear, D. R., et al., The Minerals, Metal and Materials Society, 1991, pp. 155-189.

[44] Summers, T.S.E. and J. W. Morris, Jr., "Isothermal Fatigue Behavior of Sn-Pb Solder Joints," Trans. ASME, Vol.112, June, 1990, pp. 94-112.

[45] Frear,D., Grivas, D., et al., "Fatigue and Thermal Fatigue Testing of Pb-Sn Solder Joints, "Proceedings of ASM's 3rd Conference on Electronic Packaging and Control ... in Microelectronics, 1987, pp. 269-274.

[46] Solomon, H. D., "Isothermal Fatigue of LCC/PWB Interconnections, " Presented al the ASME Winter Annual Meeting, Dec. 1-6, Atlanta, GA., 1991, 91-WA-EEP-31 .

[47] Coombs, V. D., "An Investigation of Fatigue Life Performance in Iap-Type Solder Joints," Testing for Prediction of Material Performance in Structures and Components, ASTM STP 515, 1972, pp. 3-21 (Also in IBM report TR 01.1651).

[48] Wild, R N., "Sonic Fatigue Properties of Solders and Solder Joints," IBM Report, No. 74Z00481, IBM Federal Systems Division, New York, 1975,

[49] Lake, J. K. and Wild, R N., "Some Factors Affecting Leadless Chip Carrier Solder Joint Fatigue Life," 28th National SAMPE Symp., Anaheim, CA, April 1983, pp. 1406-1414.

[50] Shine, M. C., and Fox, L, R, "Fatigue of Solder Joint in Surface Mount Devices,' Low Cycle Fatigue, STM STP 942, Edited by H. D. Solomon et al., ASTM, 1988, pp. 588-610.

[51] Kitano, M., Kawai, S., and Shimizu, T., "Thermal Fatigue Strength Estimation of Solder Joints of Surface Mount IC Packages", Proceedings 8*' Annual Int. Elect, Packaging Conf., IEPS, Dallas, TX, 1988, pp.4- 11.

[52] GUO, Q., Cutionco, E. C., Keer, L. M., and Fine, M. E., "Thermomechanical Fatigue Life Prediction of 63 Sn/37Pb Solder," J. Electronic Packaging, June 1992, Vol. 114, pp. 145-150.

[54] GUO, Z., Hacke, P., Sprecher, A. F., and Conrad, H., "Effect of Composition on the Low-Cycle Fatigue of Pb Alloy Solder Joints," Proceedings of the 40th Electronic Components and Technology Conference, May 20-23, 1990. Eas Vegas, NV, pp. 496-506.

[56] Aldrich, J. W., and Avery, D. H., "Alternating Strain Behavior of a Superplastic Metal," in Ultrafine Grain Metals, Proceedings of the 16th Sagamore Army Material Research Conference, Aug. 1969, Syracuse University Press, 1970, pp. 397-416.

[57] Enke, N. F., Kilinski, T. J., Schroeder, S. A., and Lesniak, J. R, "Mechanical Behavior of 60/40 Tin-had Solder Lap Joints," IEEE Trans. CHMT, Dec. 1989, Vol. 12, No. 4, pp. 4S9468.

[58] Vaynman, S., and Fine, M. E., "Fatigue of Low-Tin Lead-Based and Tin-Lead Eutectic Solders, " Proceedings of the 2nd ASM International Electronic Material and Processing Congress, April, 1989, pp. 255-259.

[59] Solomon, H.D.,'Life Prediction and Accelerated Testing'~ Edited by Frear, D. R, et al., Van Nostrand Reinhold, 1994, pp. 199-313.

[60] Solomon, H. D., "Fatigue of 60/40 Solder", IEEE Trans. Components, Hybrides Manufacturing Technology, Vol. CHMT-9, Dec., 1986, pp. 423-432.

[61] Solomon, H. D., "Influence of Temperature on the Fatigue of CC/PWB Joints," J. of the IES, Vol. XXXIII, No. 1, 1990, pp. 17-25.

[62] Wassink, R. J. K., "Soldering in Electronics," 2nd Edition, Electrochemical Publications Limited, 1989.

[63] Hall, P. M., "Forms, Moments and Displacements during Thermal Chamber Cycling of Leadless Ceramic Chip Carriers Soldered to Printed Wiring Boards," IEEE Transactions on Component, Hybrid and Manufacturing.l@hl~olo~, Vol. CHMT-7, No. 4, Dec. 1984, pp. 314-327.

[64] Engelmaier, W., "Fatigue Life of Leadless Chip Carrier Solder Joints During Power Cycling," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, Vol. CHMT-6, No.3, Sept. 1983, pp. 232-237.

[65] Engelmaier, W., "Surface Mount Solder Joint Long-term Reliability: Design, Testing, Prediction," Soldering and Surface Mount Technology, Vol. 1, Feb., 1989, pp. 12-22.

[66] Engelmaier, W., "Long-Term Surface Mount Solder Joint Reliability in Electronic Systems with Multiple Use Environments and a Multiplicity of Components," Advances in Electronic Packaging, EEP-Vol.4-1, ASME, pp. 479492, 1993.

[67] Engelmaier, W., "Assuring Long-Term Reliability of Surface Mount Solder Joints for Military Avionics (AVIP) Applications," Proceedings of Surface Mount International, San Jose, CA, Sept. 1993, Vol.1, pp. 376-383.

[68] Morrow, J. D., "Cyclic Plastic Strain Energy and Fatigue of Metals," ASTM STP 378, ASTM 1964, pp. 45-87.

[69] Clech, J-P. M., et al., "A Comprehensive Surface Mount Reliability Model (CSMR) Covering Several Generations of Packaging and Assembly Technology," proceedings.. of 43rd Electronic Components and Technology Conference, June 1993, pp. 62-70.

[70] Clech, J-P, et al., "A Comprehensive Surface Mount Reliability Model: Background, Validation and Applications," Proceedings of Surface Mount International, San Jose, CA, Sept. 1993, Vol.1, pp. 363-375.

[71] Sharif, I., Barker, D., Dasgupta, A., and Pecht, M., "Fatigue Analysis of a Planarpak Surface Mount Component," presented at the ASME Winter Annual Meeting, Dallas, TX, Nov. 1990, 90-WA/EEP-4; also J. Electronic Packaging, Vol. 113, June 1991, pp. 194-199.

[72] Wen, L., G.R. Men, and Ross, R. G., Jr., "Guidelines for Solder Joint Reliability Determination," JPL D-13412, June 1996.

[73] Vaynman, S., "Effect of Strain Rate on Fatigue of Low-Tin Lead-base Solder," IEEE Trans. Components, Hybrids and Manufacturing Technology, Vol. 12, No. 4, December 1989, pp. 469472.

[74] Vaynman, S., "Fatigue Life Prediction of Solder Material: Effect of Ramp Time, Hold Tim and Temperature," Proceedings of the 40th Electronic Components and Technology Conference, May 20-23, 1990, Las Vegas, NV., pp. 505-509.

[75] Solomon, H, D., "Low-Frequency, High Temperature Low Cycle Fatigue of 60Sn-40PB Solder," Presented at the Conference of Low Cycle Fatigue, Lake George, NY, Sept./Oct.]985.

[76] Solomon, H. D., "Frequency Dependent Low Cycle Fatigue Crack Propagation", Met._ T~M,, Vol. 4, 1972, pp. 34)-347.

[77] Steinberg, D. S., "Vibration Analysis for Electronic Equipment," John Wiley and Sons, 1988.

[78] Norris, K. C., and Landzberg, A. H., "Reliability of Controlled Collapse Interconnections," IBM 1. of Research and Development, pp. 266-271, May 1969.

[79] Solomon, H. D., "The Solder Joint Fatigue Life Acceleration Factor," J. Electronic Packaging, Vol. 113, pp. 186-190, June 1991.

[80] Clech, J-P., Engelmaier, W., Kotlowitz, R W., and Augis, A., "Surface Mount Solder Attachment Reliability Figures of Merit - 'Design for Reliability' Tools," Proceedings, SMART V Conference, New Orleans, LA, SMT V-48. EIA/IPC, Jan, 1989.

[81] Bayer, R G., "A New Model for Accelerated Thermal Cycle Testing with Application to TAB Leads and PCB PTHs," J. Electronic Packaging, Vol. 116, pp. 16-22, March 1994.

[82] Vaynman, S. and Zubelewicz, A., "Fatigue Life Prediction for Low-Tin Lead Based SOlder at Low Strains," Welding Research Supplement, Oct. 1990, pp. 395-398,